FELDSPATHIC METEORITES MIL 090034 AND 090070: LATE ADDITIONS TO THE LUNAR CRUST.

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Introduction: Our studies of the Miller Range lunar meteorites MIL 090034, 090036, and 090070 show them to be a diverse suite of rocks from the lunar highlands [1,2,3] hereafter referred to as MIL 34, MIL 36, and MIL 70, resp. MIL34 and MIL70, the focus of this work, are crystalline melt breccias. Plagioclase compositions in both peak sharply around An_{96-97}. Mg numbers of olivine vary from 58-65 with a few higher values [1]. MIL36 is a regolith breccia.

MIL 34 and MIL 70 have some of the highest Al_2O_3 abundances of lunar highland meteorites, indicating that they have among the largest modal abundances of plagioclase for lunar meteorites. They have lower Sc and Cr abundances than nearly all lunar highland meteorites except Dho 081, Dho 489 and Dho 733 [2].

MIL34 and MIL70 also have similar cosmic ray exposure (CRE) ages of ~1-2 Ma indicating they are launch paired [3]. (MIL36 has a larger CRE age ~>70 Ma). Park et al. [3,4] found a variation in Ar-Ar ages among subsamples of MIL 34 and MIL70, but preferred ages of 3500±110 Ma for the “Dark” phase of MIL 34 anorthite and 3520±30 Ma for the "Light" phase of MIL70. Bouvier et al. [5] reported a Pb-Pb age of 3894±39 Ma for a feldspathic clast of MIL 34 and a similar age for a melt lithology.

Here we reexamine the Rb-Sr and Sm-Nd isotopic data [6], which show complexities qualitatively consistent with those of the Ar-Ar and Pb-Pb data. The Sm-Nd data in particular suggest that the feldspathic compositions of MIL 34 and MIL 70 formed during initial lunar geochemical differentiation, and REE modeling suggests a relatively late-stage formation.

Rb-Sr isotopic data: Figure 1 shows Rb-Sr data for plagioclase density-separated ($\rho < 2.85$ g/cm^3) from MIL 34 and 70 in comparison to data for some Apollo 16 anorthosites. These data perhaps are best interpreted as showing some Rb-loss during the event(s) recorded by the Ar-Ar and Pb-Pb ages. Comparing to the reference Rb-Sr isochron for ferroan anorthosite (FAN) 67075 [7] suggests that the undisturbed value of $^{87}Rb/^{86}Sr$ for pre-cursor lithologies (if FAN) would have been in the range ~0.010-0.012, significantly higher than for most other lunar anorthosites. An increase in the Rb/Sr ratio is characteristic of increasingly differentiated lunar lithologies, and suggests that the precursors of the MIL 34 and MIL 70 samples were more highly differentiated than most lunar anorthosites.

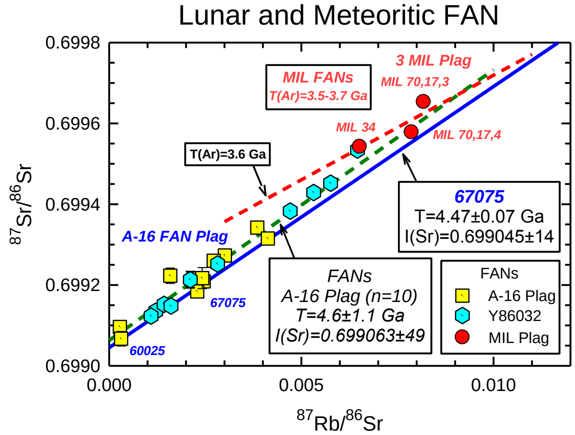

Figure 1. Rb-Sr isotopic data for MIL 34 and MIL 70.

REE abundances: On a plot of FeO vs. Al_2O_3, MIL 34 and MIL 70 plot at the high-Al_2O_3/low-FeO end of an oval-shaped “troctolite” field [2,4] with slightly higher values of both parameters than Dho 489, the prototypical magnesian anorthosite (MAN) [8]. However, high Al_2O_3 (30%) and CaO(16%) abundances, and low MgO (2.5%) preclude a troctolitic composition. The major element abundances correspond to >80% normative plagioclase and place both samples into the noritic/gabbroic anorthosite field in the rock classification diagrams used by [9] to classify lunar central peak compositions.

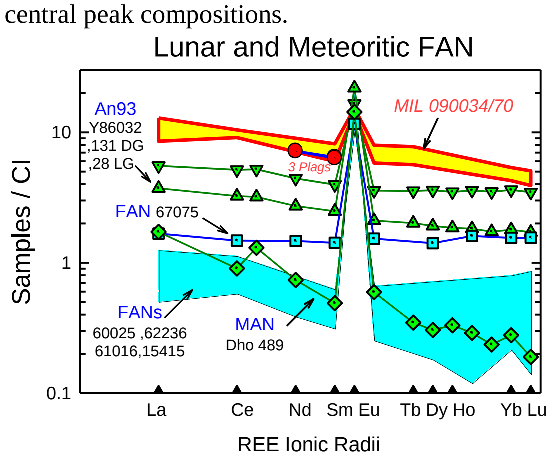

Figure 2. REE abundances in MIL 34, MIL 70, and density-separated plagioclase from them compared to REE in other lunar anorthosites.

On a plot of Sm vs. Sc, MIL 34 and MIL 70 are shown to have low Sc abundances, rivaling those of Dho 489, but with Sm abundances ~6x those in Dho 489 samples [2]. On a plot of Sm vs. Cr they occupy positions similar to those for several Apollo-sample troctolite clasts. They have generally higher Sc abundances than these same clasts, however, consistent with normative mineral abundances placing them into the gabbroic anorthosite region of the rock classification scheme [9]. Figure 2 shows that REE abundances are higher than for a suite of lunar anorthosites, but plausibly can be considered as part of a regularly increasing progression. Importantly, Nd and Sm in the density separates are very similar to those in bulk samples suggesting only minor REE contributions from extraneous sources to these breccias, if any at all.

Sm-Nd isotopic data: Sm-Nd data for density-separated plagioclase from MIL 34 and MIL 70 are shown in Figure 3. These data lie along reference isochrons for Y86032 (4.43±0.03 Ga [10,11]) and 67075 (4.47±0.07 Ga [7]), if some allowance is made for post-crystallization disturbance recorded in the other isotopoic systems also. The rocks represented plausibly can be assumed to have been co-magmatic.

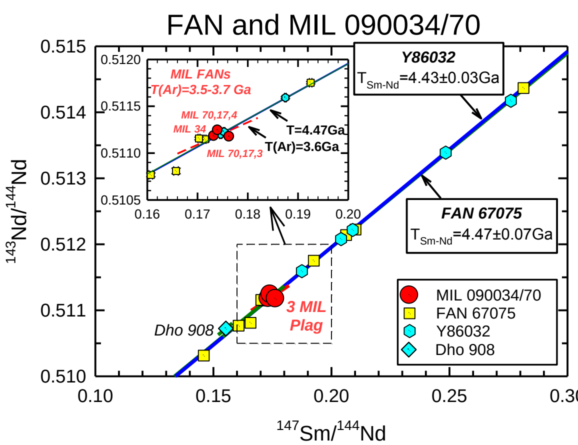

Figure 3. Sm-Nd data for density-separated plagioclase from MIL 34 and MIL 70 compared to mineral isochrons for 67075 and Y86032. Bulk rock data for Dho 908 of the Dho 489 family also are shown.

REE modeling: In Fig. 4, the REE abundances and distribution patterns of MIL 090034/70 are shown as open red circles bordering the yellow band; red solid circles show Sm and Nd abundances for the three density-separated plagioclase samples. Blue open squares show the REE pattern for a melt after 95% solidification (PCS=95%) of the LMO following [12]. According to this model, a 95 PCS melt would become saturated with plagioclase, clinopyroxene, pigeonite and ilmenite at a late stage of magma differentiation. The blue hexagons represent REE abundances for pure plagioclase (i.e., "PAN") crystallized from such a melt. The blue open triangles represent such a late-stage cumulate retaining 8% trapped interstitial melt. That the REE pattern for this assemblage resembles those of MIL 34/70, suggests that the precursor rocks could have contained late-stage plagioclase cumulates from the LMO.

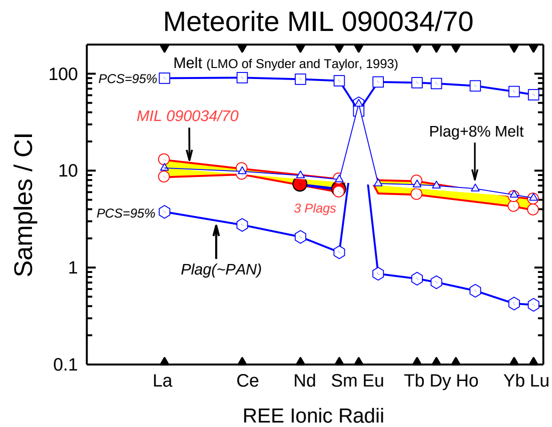

Figure 4. REE modelling of a simple petrogenesis model for the precursors of MIL 090034/70.

Conclusions: The ~95% PCS model yields a pure plagioclase cumulate (PAN) with Sm ~1.4 times CI chondrites. Modeling MAN Dho 489, FAN 15415, and Apollo 16 FANs with similar REE abundances (Sm ~0.35 x CI) can be accomplished for an earlier, ~78 PCS LMO. (Not shown). The MIL 34/70 precursor rocks formed later in the LMO crystallization sequence than did these REE-depleted anorthosites, but probably are more representative of the lunar crust. Korotev [13] estimated the average Sm concentration of the plutonic rocks of the early feldspathic lunar crust to have been ~2-3 x CI abundances. PAN exposed in the central peaks of modest-sized craters (*cf.* [9]) may be more closely related to PAN crystallized from a 95-PCS-like magma than to PAN from a 78-PCS-like magma.

References: [1] Yamaguchi A. et al. (2013) *Mineralogical Magazine*, 77(5) 2539 [2] Shirai N. et al. (2012) *LPS 43*, Abstract #2003. [3] Park J. et al. (2013) *LPS 44*, Abstract #2576. [4] Park J. et al. (2015) *MetSoc 78*, Abstract #5237. [5] Bouvier A. et al. (2013) *MetSoc 76*, Abstract #5312. [6] Nyquist L. et al. (2014) *LPS 45*, Abstract #1125. [7] Nyquist L. et al. (2010) *LPS 41*, Abstract #1383. [8] Takeda H. et al. (2006) *Earth Planet. Sci. Lett. 247,* 171–184. [9] Lemellin M. et al. (2015) *J. Geophys. Res. Planets, 120,* 869-887. [10] Nyquist L. et al. (2006) *Geochim. Cosmochim. Acta* 70, 5990–6015. [11] Yamaguchi A., et al. (2010) *Geochim. Cosmochim. Acta 74,* 4507-4530. [12] Snyder G. A. and Taylor L. A. (1993) *Proc. NIPR Symp. Antarctic Meteorites 6,* 246-267. [13] Korotev R. L. (2006) *Geochim. Cosmochim. Acta 70,* 5935--5956.